Proton Irradiation Effects on Strained $Si_{1-x}Ge_x$/Si Heterostructures

J. S. Park, T. L. Lin, E. W. Jones, S. D. Gunapala, G. A. Soli and B. A. Wilson

Center for Space Microelectronics Technology
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA 91109

ABSTRACT

Proton irradiation effects on strained $Si_{1-x}Ge_x$/Si heterostructures have been studied. For the experiment, p^+-$Si_{1-x}Ge_x$/p^--Si heterojunction diodes were fabricated by molecular beam epitax y (MBE) growth of strained p^+- boron doped SiGe layers on p^--Si(100) substrates. Due to the valence band discontinuity between SiGe and Si layers, and degenerate doping in the SiGe layer, the characteristics of these heterojunction diodes are similar to those of metal-semiconductor Schottky barrier diodes. The SiGe/Si heterojunction diodes are irradiated by 1 Mrad of protons at 1 and 8.5 MeV energies. The current-voltage (I-V) characteristics are measured as a function of temperature before and after irradiation. I-V characteristics show a decrease of the reverse bias leakage current after irradiation. The effective heterojunction barrier heights (Φ_b) and Richardson constants (A^{**}) are measured before and after irradiation using activation energy measurements. The measurements show an increase of Φ_b and A^{**} after irradiation. The "increase of the effective barrier height is attributed to reduction of free holes in the SiGe layers due to proton induced displacement defects. The increase of effective barrier height suggests that the strain in the SiGe layers is conserved after 1 Mrad of proton irradiation.

Strained $Si_{1-x}Ge_x/Si$ heterostructure have created a great deal of interest in recent years for novel device applications such as heterojunction bipolar transistors (HBT),[1,2] modulation doped field effect transistors (MODFET),[3,4] resonant tunneling diodes,[5,6] resonant tunneling transistors and long wavelength infrared detectors.[8-12] These devices can be monolithically integrated with silicon VLSI circuits for many applications, such as high speed circuits, opto-electronics and infrared focal plane arrays. However, limited study has been done in the area of the radiation associated reliability of strained SiGe/Si devices. In this letter, we report 1 Mrad proton irradiation effects on strained p^+-SiGe/p^--Si heterostructures.

For the experiment, p^+-$Si_{1-x}Ge_x$/p^--Si heterojunction diodes were fabricated by MBE growth of p^+-$Si_{1-x}Ge_x$ layers on oxide patterned p^--Si(1 00) wafers with resistivity of 30 Ω-cm. Due to the valence band discontinuity between SiGe and Si layers, and degenerate doping in the SiGe layer, the characteristics of these heterojunction diodes are similar to those of metal-semiconductor Schottky barrier diodes. Figures 1 (a) and (b) show the device structure and the energy band diagram of the p^+-$Si_{1-x}Ge_x$/p^--Si heterojunction diode used for the experiment. The diode structure incorporates a p^+-substrate contact and n-type guard rings which define the periphery of the active device areas to suppress edge leakage. The boron doped SiGe layers were grown at 350 ‘C in a Riber EVA 32 Si MBE system. For heavy boron doping an elementary boron source (using a high temperature effusion cell) was used. The details of MBE growth and boron doping can be found in Ref.9. Two diodes with different structure were fabricated. The first diode (diode A) structure consists of a strained $5x10^{19}$ cm^{-3} boron doped 300 Å $Si_{0.6}Ge_{0.4}$ layer grown on a Si substrate; and the second diode (diode B) structure consists of a strained 1 $x10^{20}$ cm^{-3} boron doped 100 Å $Si_{0.7}Ge_{0.3}$ layer grown on a Si substrate. In this structure due to strain, the degenerate valence band of $Si_{1-x}Ge_x$ layer splits into heavy and light hole bands as shown in Fig. 1(b). Because of degenerate p-doping, the Fermi-level (E_f) is located below the valence band edge in the SiGe layer. The effective heterojunction barrier height (@b) is determined by the energy difference between the valence band-offset (ΔE_v) and the Fermi-level (ΔE_v - E_f). In early publications, we demonstrated that this type of structure exhibits tailorable photoresponse in the long wavelength infrared regime, and named it the SiGe/Si heterojunction internal photoemission (HIP) detector.[8,9]

For irradiation, the proton accelerator at the California Institute of Technology was used. The SiGe/Si heterojunction diodes were mounted on chip carriers and were irradiated at room temperature by approximately 1 Mrad of monoenergetic beams protons with energies of 1 and 8.5 MeV. The proton beams were incident normally on the front side of the diodes. The current-voltage (I-V) characteristics of the diodes before and after irradiation were measured at several temperatures, Figures 2(a) and (b) show the reverse bias leakage current characteristics of diodes A and B before and after irradiation. As shown in Figs. 2, a decrease of leakage current is observed after proton irradiation, and a larger decrease is observed with 1 MeV protons than with 8.5 MeV protons.

In order to understand the measured I-V characteristics before and after irradiation, the current mechanisms for the present SiGe/Si diodes should be considered. Due to the degenerate doping in the SiGe layers, our SiGe/Si diodes are similar to a metal Schottky barrier diodes where the thermionic-emission current is the major current component. The thermionic-emission current (J) at reverse bias is given by[13]

$$J = A^{**} T^2 \exp(-q\Phi_b/kT),$$

where Φ_b is the effective heterojunction barrier height, A^{**} is the Richardson constant, T is the temperature and k is Boltzmann constant. The values of Φ_b and A^{**} can be experimentally determined by the activation energy analysis (by measuring reverse J-V at various temperatures and plotting $\mathrm{LN}(J/T^2)$ vs. $1/kT$). Figure 3 shows examples of $\mathrm{LN}(J/T^2)$ vs. $1/kT$ plots for the diode A before and after 8 and 1 MeV proton irradiation at -0.1 V reverse bias. From the slope of the linear portion of the plot, the effective barrier heights are obtained. Also, from the ordinate intercept at $1/kT = 0$, A^{**} can be determined. The effective barrier height and Richardson constants were measured at several reverse biases between 0.05 and 0.5 V. Then, the values at zero bias are obtained by extrapolation. The experimentally measured $\Phi_b(0)$ and $A^{**}(0)$ for diodes A and B are listed in Table I. The measured effective barrier heights are much smaller than the calculated valence band-offsets between Si and $Si_{1-x}Ge_x$ by People *et. al*.[14] This is because of the Fermi-1evel shift due to heavy boron doping. For the diode A, $\Phi_b(0)$'s of 174, 182 and 185 meV, respectively are obtained before any irradiation and after 8.5 and 1.0 MeV proton irradiation. For diode B, $\Phi_b(0)$'s of 57 and 62 meV are obtained before and after 8.5 MeV irradiation. However, in the 1 MeV irradiation case for diode B, no linear region existed in the activation energy plot, thus the effective barrier height could not be estimated.

Thus, we observed that the effective barrier heights (@b) increase after irradiation and further increase as the proton energy decreases. This first implies that the strain in the $Si_{1-x}Ge_x$ layers is conserved after irradiation. If the strain in a SiGe layer were relaxed, the SiGe layer would resume its bulk lattice constant by generating misfit dislocations. In this case, the SiGe bandgap increases and the valence band-offset between the SiGe and the Si substrate is expected to be reduced. For example, ΔE_v of an undoped strained $Si_{0.6}Ge_{0.4}$ on Si(100) is about 0.3 eV,[4,15] while AE_v of bulk SiGe on Si(100) is about 0.11 eV (this value is obtained from the linear interpolation of AE_v of bulk Ge on Si(100)[16]). The proton irradiation effect on the strain of SiGe layers will be further investigated by transmission electron microscopy (TEM) and X-ray studies.

The Richardson constant A^{**} can be determined from the ordinate intercept at 1/kT= O. The measured values are about 13 $A/cm^2/K^2$ for both diode A and B before irradiation. This value increases to 30 and 33 $A/cm^2/K^2$ after 8.5 and 1.0 MeV irradiation for diode A, respectively; and increases to 25 $A/cm^2/K^2$ after 8.5 MeV irradiation for diode B. The increase of A^{**} suggests device degradation after proton irradiation, such as defect generation which creates additional tunneling and generation-recombination currents.

It is well known that when fast incident protons (or neutrons) collide with the lattice atoms in semiconductors, they can displace them from their lattice sites (creating vacancies) and move them to interstitial positions. This displacement damage by protons produces a number of trapping defect complexes in semiconductors. And these complexes capture majority carriers and effectively compensate dopant atoms. The effective barrier height increase after proton irradiation is attributed to the reduction of free holes in the SiGe layers due to proton induced displacement damage. The increase of A** after irradiation is also due to the proton induced damages. Both parameters which govern the thermionic-emission current increase after irradiation. However, since the leakage current is exponentially dependent on - Φ_b, a small increase of Φ_b, even with an increase of A^{**}, can significantly decrease the leakage current. Therefore, the experimentally observed leakage current decrease after proton irradiation for our SiGe/Si diodes can be understood.

The number of reduced holes after irradiation can be estimated from the hole concentrations before and after irradiation. The carrier concentrations before and after irradiation can be calculated from the experimentally obtained Φ_b's. The hole concentration for the degenerately doped strained SiGe layers are determined by

$$p = N_{V,HH} \frac{2}{\sqrt{\pi}} F_{1/2}(\frac{E_{HH} - E_f}{kT}) + N_{V,LH} \frac{2}{\sqrt{\pi}} F_{1/2}(\frac{E_{LH} - E_f}{kT})$$

where $N_{v,HH}$ and $N_{v,LH}$ are the effective density of states of heavy and light holes, respectively; and $F_{1/2}$ is the Fermi-Dirac integral, E_f is the Fermi level and E_{HH} and E_{LH} are the heavy and light hole band edges, respectively. Because of the valence band splitting the carrier concentration in the heavy and light hole bands should be calculated separately. As shown in Fig. 1(b), the Fermi energy (E_f) can be estimated by $AE_v - q\Phi_b$. The valence band-offset ΔE_v and heavy-light hole splitting energy are calculated according to Ref. 14 and Φ_b is experimentally estimated (values listed in Table I). The heavy and light hole effective masses are approximated by the linear interpolation of bulk Si and Ge effective masses. Using the above equation and values, we obtained hole concentrations of 5.4x10'9, 4.8x1019 and 4.7x1019 cm^{-3} for diode A before, and after irradiation at 8.5 and 1.0 MeV, respectively; and 9.4x1019 and $8.9x10^{19}$ cm^{-3} for diode B before and after irradiation at 8.5 MeV. Thus, a hole concentration of about 5-6x1018 cm^{-3} is estimated to be reduced after a 1 Mrad proton irradiation.

The proton energy dependent J-V characteristics and effective barrier height change (decrease of leakage current and increase of barrier height and A^{**} with the proton energy) indicate that lower energy protons create more damages in our SiGe/Si structures. This is understandable because the lower energy protons, due to shorter penetration depth and larger collision cross section, create more displacement damages near the top layer where the active SiGe layers are positioned. Similar proton energy dependence on displacement damages were reported theoretically [17] as well as experimentally for using Si charge coupled devices[18].

In summary, we have studied proton irradiation effects on strained p^+-SiGe/p^--Si heterostructures. The reverse bias current voltage characteristics of the SiGe/Si heterojunction diodes showed a decrease of current after a 1 Mrad proton irradiation. The effective SiGe/Si barrier heights and Richardson constants were estimated by activation energy measurements, and the results showed an increase of both parameters after irradiation. The leakage current decrease after irradiation was attributed to the barrier height increase, which was caused by the proton induced free carrier reduction. The increase of the barrier height further suggests that the strain in SiGe layer is not relaxed after a 1 Mrad proton irradiation.

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FIGURE CAPTIONS

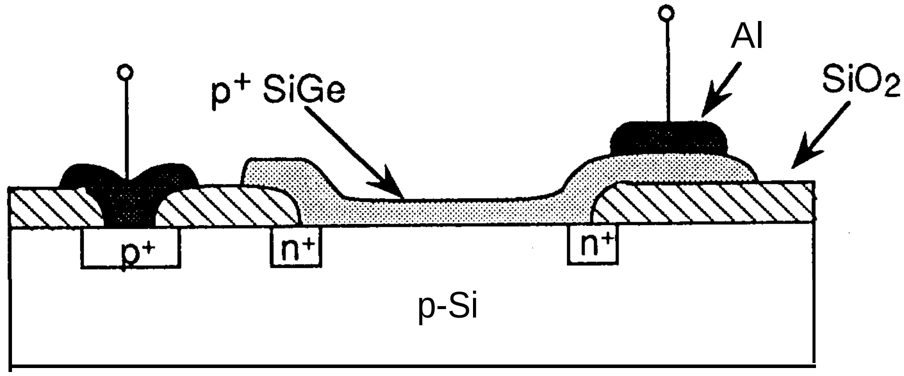
Figure 1. (a) Schematic cross-section and (b) energy band diagram of the strained p^+-SiGe/p^--Si heterojunction diodes.

Figure 2. The reverse bias current-voltage (I-V) characteristics of diode A (a) and diode B (b) before any irradiation and after a 1 Mrad proton irradiation at 8.5 and 1 MeV energies.

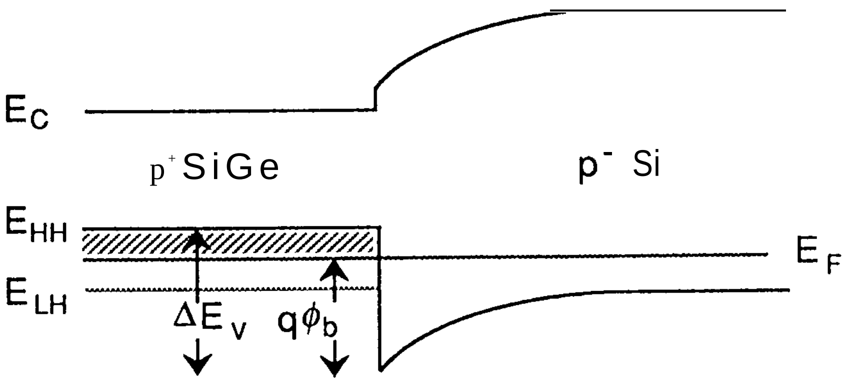
Figure 3. Activation energy plots ($LN(J/T^2)$ vs. $1/kT$) for diode A at -0.1 V bias (a) before any irradiation and after a 1 Mrad proton irradiation at (b) 8.5 MeV and (c) 1 MeV energies.

Table I. The measured effective barrier heights and Richardson constants for diodes A and B.

	Diode A		Diode B	
	Φ_b (meV)	A^{**} ($A\ cm^{-2}\ K^{-2}$)	Φ_b (meV)	A^{**} ($A\ cm^{-2}\ K^{-2}$)
Before Irradiation	174	13	57	13
After 1 Mrad @ 8.5 MeV	182	30	62	25
After 1 Mrad @ 1.0 MeV	185	33		—



(a)



(b)

Fig. 1

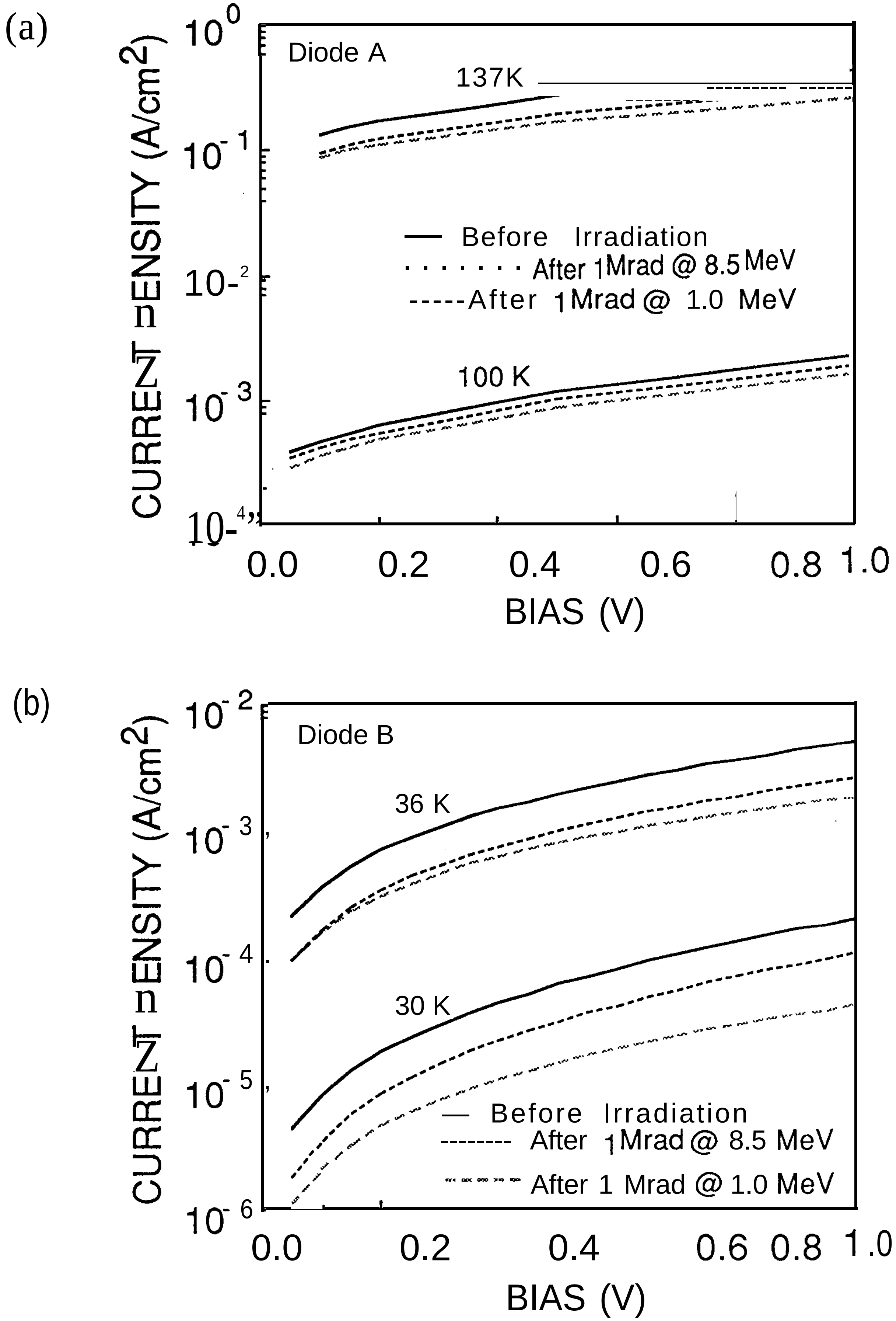

(a)
Diode A
137K
100 K
Before Irradiation
After 1Mrad @ 8.5 MeV
After 1Mrad @ 1.0 MeV
CURRENT DENSITY (A/cm2)
BIAS (V)
(b)
Diode B
36 K
30 K
Before Irradiation
After 1Mrad @ 8.5 MeV
After 1 Mrad @ 1.0 MeV
CURRENT DENSITY (A/cm2)
BIAS (V)

Fig. 2

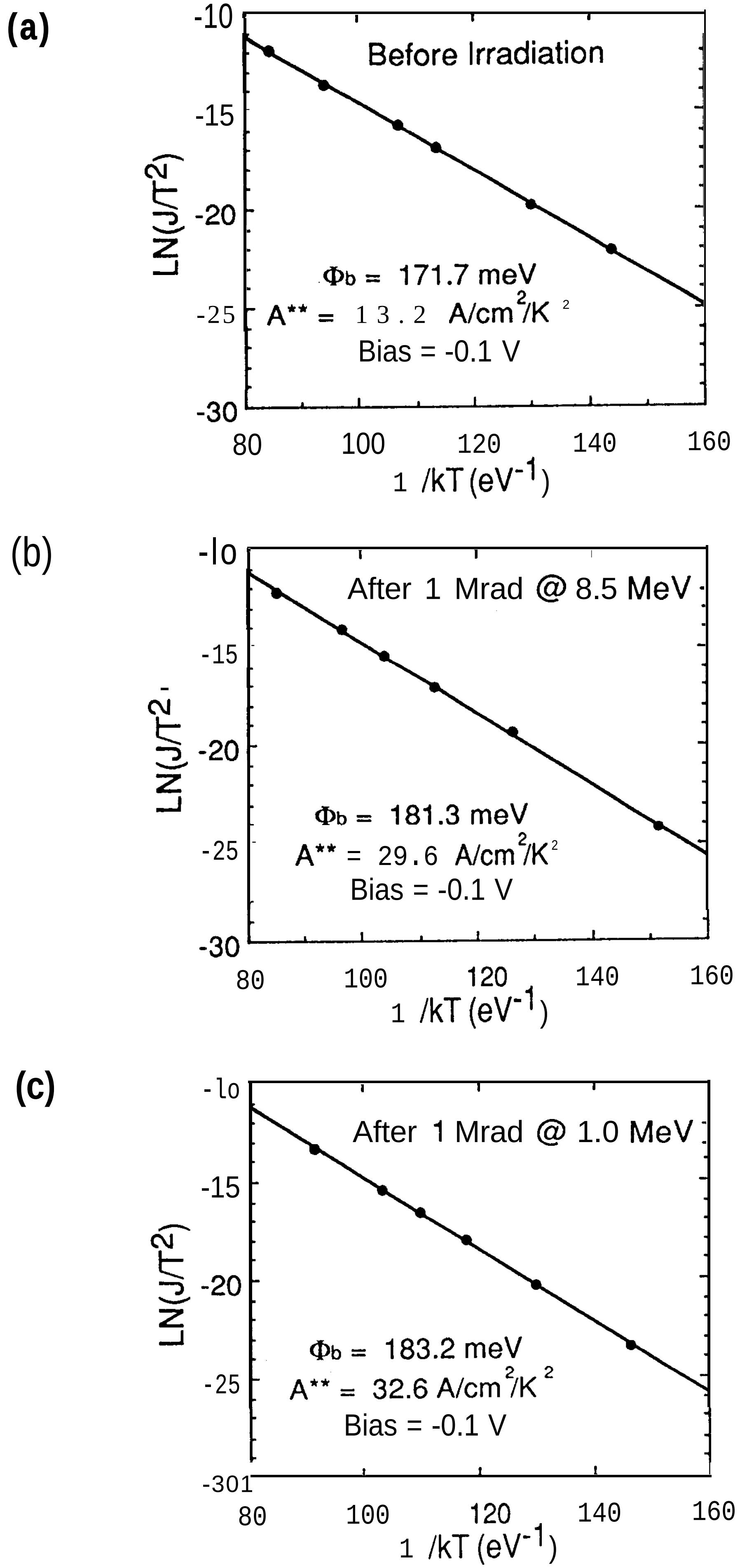

(a)
Before Irradiation
Φb = 171.7 meV
A** = 13.2 A/cm2/K 2
Bias = -0.1 V
LN(J/T2)
1 /kT (eV-1)
(b)
After 1 Mrad @ 8.5 MeV
Φb = 181.3 meV
A** = 29.6 A/cm2/K2
Bias = -0.1 V
LN(J/T2
1 /kT (eV-1)
(c)
After 1 Mrad @ 1.0 MeV
Φb = 183.2 meV
A** = 32.6 A/cm2/K 2
Bias = -0.1 V
LN(J/T2)
1 /kT (eV-1)

Fig. 3